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From ENSEMBLES to CORDEX: Evolving climate change projections for Upper Danube River flow

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ABSTRACT

Regional Climate Models (RCMs) generate past and future climate simulations that serve as input for subsequent modelling of impact projections. The most recent coordinated regional climate modelling initiative, CORDEX, provides RCM data for Europe with increased spatial resolution (12.5 km for the CORDEX EUR-11 ensemble) and based on the new Representative Concentration Pathways (RCPs). RCM data from the previous initiative ENSEMBLES had a spatial resolution of 25 km and was based on the SRES emission scenarios. In this contribution we explore the development from ENSEMBLES to CORDEX in a hydrological impact study for the Upper Danube, focussing on the representation of past climate and projections of the future for climate and resulting river discharge. We replicated a hydrological modelling framework, including RCM downscaling and bias correction, that used data of 21 ENSEMBLES RCMs under SRES A1B emission scenario (Kling et al., 2012), and now applied CORDEX EUR-11 data of 32 RCM simulations under RCP4.5 and RCP8.5 emission scenarios. Results with CORDEX show a small improvement in the representation of historical precipitation, but a decline in the accuracy of historical temperature simulations, despite the increase in spatial model resolution. The tendency of ENSEMBLES climate projections is reproduced with the CORDEX RCMs, albeit with slightly higher precipitation in the CORDEX data, yielding a less pronounced reduction in future mean annual discharge for the Upper Danube at Vienna. The previously identified change in discharge seasonality – increasing winter discharge and decreasing summer discharge – is confirmed with the new CORDEX data. Updating climate impact simulations in the presented rigorous replication framework allows analysing specific new information in the latest generation climate model data as well as crystallizing essential expectable patterns of change that need to be addressed in adaptation strategies.

1. Introduction

The Danube River is the second largest and second longest European river, crossing 10 countries and draining areas that belong to 19 countries in the historically turbulent and culturally diverse Central and Southeast European regions. The Danube is an important inland waterway and provides enormous economic value for diverse sectors as hydropower, water supply, irrigation and tourism. Its water and the large variety of habitats along its course sustain an immense ecological diversity. The upper Danube basin with its mainly alpine catchment area is a water tower for the entire Danube, providing around 30% of its discharge at the mouth at the Black Sea from around 13% of the catchment area, and seasonally contributing to higher flows through the drier summers in Southeast Europe. For a concise overview of general facts and figures on the Danube basin refer to ICPDR (2011). Comprehensive elaborations on hydrological processes and water management in the Danube basin are provided by ICPDR (2005) and Brilly (2010).

Due to this manifold importance of the Danube River, possible changes in its discharge regime triggered by global climate change have been subject of hydrological climate change impact research for many years, with several studies focussing on the snow-dominated Upper Danube catchment with its high sensitivity to warming. Climate impact studies based on global hydrological models and projections from Global Climate Models (GCMs) by Arnell (1999), Lehner et al. (2006), Nohara et al. (2006) and Sperna-Weiland et al. (2012) presented results for the Danube. GCM data were also applied in a water balance analysis for the Danube basin by Lucarini et al. (2008) and used for stochastic climate generation as input for hydrological modelling by Mauser and Bach (2009). Acknowledging the need of climate simulations at higher spatial resolution than available from GCMs for relevant hydrological impact research, following studies applied climate data of one or several Regional Climate Models (RCMs) from subsequent model generations (Hagemann and Jacob 2007; Stanzel and Nachtnebel 2010; Prasch et al., 2011; Koch et al., 2011; Blöschl et al., 2011; Wagner et al., 2017). Applying large ensembles of RCM data, Kling et al. (2012) and Stagl

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and Hattermann (2015) also investigated the uncertainty in climate impact scenarios due to the range of potential climate model projections.

The continuous elaboration of hydrological climate change impact scenarios for the Danube River has been stimulated by advances in regional climate modelling. Updated climate simulations for Europe from subsequent RCM generations have been triggered by and coordinated in three large initiatives, PRUDENCE (Christensen and Christensen 2007), ENSEMBLES (Hewitt and Griggs 2004), and CORDEX (Giorgi et al., 2009). One main development was the ongoing increase in horizontal model resolution, from 50 km in PRUDENCE to 25 km in ENSEMBLES to 12.5 km in the latest generation high-resolution RCM simulations of the CORDEX EUR-11 ensemble (Jacob et al., 2014). This paper describes the first application of CORDEX EUR-11 climate data, the most advanced RCM ensemble available for Europe, to update the climate change projections for the Upper Danube basin.

The progress in climate modelling from one generation of climate models to the next is regularly investigated (e.g. Knutti and Sedlacek 2013; Ylhäisi et al., 2015 for GCMs; Deque et al., 2012; Kotlarski et al., 2014; Smiatek et al., 2016 for RCMs). A singular long-term chronology of the development of climate projections was presented by Whetton et al. (2016) for Australia. Different results of hydrological impact based on different assessment methods and generations of climate model data were compiled in review articles (e.g. Roudier et al., 2014 for West Africa, Di Baldassarre et al., 2011 for the Nile Basin), but without a focus on the development of knowledge over time.

The presented study attempts, for the first time to our knowledge, a detailed exploration of the development of hydrological impact scenarios resulting from the evolution of climate simulations from one generation of climate models to the next. In a rigorous replication experiment, we applied exactly the same methodology in climate data processing and hydrological modelling as described in Kling et al. (2012), replacing the data of 21 RCMs of the ENSEMBLES initiative with simulations of 16 RCMs of the CORDEX initiative. Development from ENSEMBLES to CORDEX can be expected due to increased spatial resolution – from 25 km in ENSEMBLES to 12.5 km in the applied CORDEX EUR-11 simulations –, due to changes in the assumed greenhouse gas emission scenarios – from the SRES A1B scenario (Nakicenovic et al., 2000) in the applied ENSEMBLES data to Representative Concentration Pathways RCPs (Moss et al., 2010) in the CORDEX scenarios –, and due to general climate model development (Ylhäisi et al., 2015).

The objectives of this study are (1) to derive updated climate impact scenarios for the Upper Danube River based on the latest generation of high-resolution RCMs from the CORDEX initiative for Europe and (2) to investigate the differences compared with previous results with ENSEMBLES data. The development from ENSEMBLES to CORDEX is analysed with respect to:

- representation of past climate in the Upper Danube basin, focusing on temperature and precipitation as the main drivers of hydrological impact;
- projections for future climate;
- the related impacts on Danube River discharge at Vienna and at selected tributaries.

The structure of this paper generally follows the structure of the original ENSEMBLES article by Kling et al. (2012), without repeating details of unchanged methods, data and results. Section 2 outlines the study area; Section 3 describes the applied climate model data; Section 4 shortly recapitulates the methods of modelling and analyses; Section 5 presents the results with the new CORDEX data and shows comparisons with ENSEMBLES results; Section 6 provides a discussion of the main findings, of research questions remaining open, and of implications for water management; Section 7 gives a concise summary of the presented study and proposes some main conclusions.

2. Study area

This study focuses on the Danube River at Vienna, which has an upstream catchment area of 101810 km^2 (Fig. 1). The observed mean annual discharge in the period 1961–1990 was 1923 m^3/s. There is a

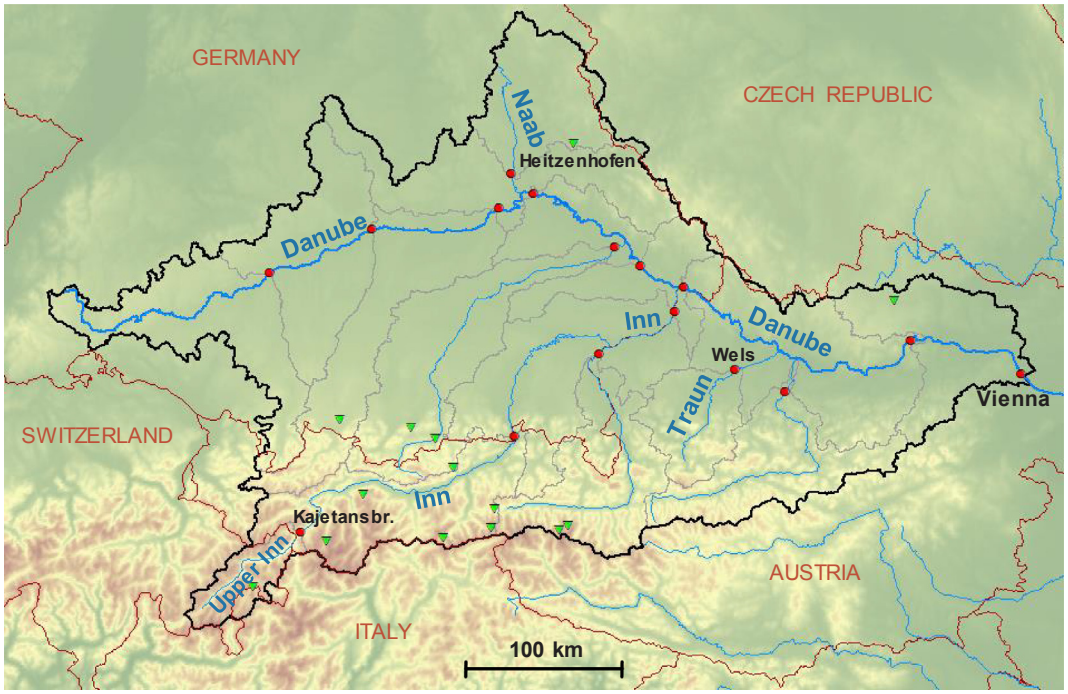


Fig. 1. Study area Upper Danube basin upstream of Vienna. Black lines: basin divides. Grey lines: sub-basin divides. Blue lines: major rivers in Danube basin. Red lines: country borders. Red circles: used gauges. Green triangles: large reservoirs considered in the model. Background colour: digital elevation model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

strong seasonality in discharge due to accumulation and melting of snow in the alpine, southern parts of the basin. Annual precipitation is higher in the alpine parts than in the pre-alpine and lowland areas in the northern and eastern parts of the basin. Precipitation in summer is larger than in winter. The basin-averaged annual precipitation amounts to approximately 1100 mm, which is roughly split equally into runoff and actual evapotranspiration. More details about the study area and the water balance of the basin are given in Kling et al. (2012).

Specific results are also presented for three smaller tributary catchments that represent different regions and hydrological regimes within the basin: the Upper Inn (at Kajetansbrücke, 2157 km^2) in the highest Alpine region in Switzerland, the lowland Naab (at Heitzenhofen, 5415 km^2) in Germany, and the Traun (at Wels, 3505 km^2), located in the Austrian lower Alps and alpine foothills.

3. Climate model data

The climate model data used for the new analyses presented here are the recent results of the global CORDEX initiative (Giorgi et al., 2009) for Europe (EURO-CORDEX, Jacob et al., 2014), as available via the data portals of the Earth System Grid Federation (ESGF) in September 2016. EURO-CORDEX RCM simulations are provided with a spatial resolution of 50 km (corresponding to 0.44°, therefore called EUR-44) and with a higher spatial resolution of 12.5 km (0.11°, therefore called EUR-11). For this study, only EUR-11 CORDEX simulations were applied (listed in the upper part of Table 1), as they provide an increased spatial resolution compared with the ENSEMBLES data. The 21 applied ENSEMBLES climate model simulations (listed in the lower part of Table 1) have a spatial resolution of 25 km (for more details on the used ENSEMBLES data refer to Kling et al., 2012).

Table 1
Regional Climate Model data considered in this study (16 CORDEX RCMs, applied now, and 21 ENSEMBLES RCMs applied by Kling et al. in 2012). The last column lists a measure of model performance (MP) for the representation of observed climate (with smaller values indicating better performance).

Acronym	Institute	RCM	GCM	MP [/]
CORDEX: 12.5 km				
CLMcom_CNRM	CLMcom	CCLM4-8-17	CERFACS-CNRM-CM5	0.90
CLMcom_ICHEC	CLMcom	CCLM4-8-17	EC-EARTH	0.77
CLMcom_MOHC	CLMcom	CCLM4-8-17	HadGEM2-ES	0.93
CLMcom_MPI	CLMcom	CCLM4-8-17	M-MPI-ESM-LR	0.93
SMHI_CNRM	SMHI	RCA4	CERFACS-CNRM-CM5	1.23
SMHI_ICHEC	SMHI	RCA4	EC-EARTH	1.08
SMHI_MOHC	SMHI	RCA4	HadGEM2-ES	1.01
SMHI_MPI	SMHI	RCA4	M-MPI-ESM-LR	1.04
SMHI_IPSL	SMHI	RCA4	IPSL-CM5A-MR	1.21
KNMI_ICHEC	KNMI	RACMO22E	EC-EARTH	1.10
KNMI_MOHC	KNMI	RACMO22E	HadGEM2-ES	1.01
DMI_ICHEC	DMI	HIRHAM5	EC-EARTH	1.07
IPSL_IPSL	IPSL	WRF331F	IPSL-CM5A-MR	1.29
CNRM_CNRM	CNRM	ALADIN53	CERFACS-CNRM-CM5	1.04
MPI_MPIr1	MPI	REMO2009	M-MPI-ESM-LR r1i1p1	0.87
MPI_MPIr2	MPI	REMO2009	M-MPI-ESM-LR r2i1p1	0.84
ENSEMBLES: 25 km				
C4IRCA3	C4I	RCA3	HadCM3Q16	1.03
CNRM-RM45	CNRM	Aladin	ARPEGE	0.84
CNRM-RM51	CNRM	Aladin	ARPEGE_RM51	0.97
DMI-ARPEGE	DMI	HIRHAM	ARPEGE	1.53
DMI-BCM	DMI	HIRHAM	BCM	1.22
DMI-ECHAM5	DMI	HIRHAM	ECHAM5-r3	1.34
ETHZ	ETHZ	CLM	HadCM3Q0	0.98
GKSS	GKSS	CLM	IPSL	1.26
ICTP	ICTP	RegCM	ECHAM5-r3	0.89
KNMI	KNMI	RACMO	ECHAM5-r3	0.82
KNMI50km	KNMI	RACMO	MIROC	0.91
METNO-BCM	METNO	HIRHAM	BCM	1.21
METNO-HAD	METNO	HIRHAM	HadCM3Q0	1.01
METO	HC	HadRM3Q0	HadCM3Q0	0.96
METO-Q3	HC	HadRM3Q3	HadCM3Q3	1.20
METO-Q16	HC	HadRM3Q16	HadCM3Q16	1.50
MPI	MPI	REMO	ECHAM5-r3	0.78
SMHIRCA-BCM	SMHI	RCA3	BCM	1.09
SMHIRCA-ECH	SMHI	RCA3	ECHAM5-r3	1.04
SMHIRCA-HAD	SMHI	RCA3	HadCM3Q3	1.05
UCLM	UCLM	PROMES	HadCM3Q0	1.01

In addition to RCM resolution, different greenhouse gas emission scenarios are a major difference between the climate simulations of ENSEMBLES and CORDEX models. While the analysed ENSEMBLES projections are based on the SRES A1B scenario (Nakicenovic et al., 2000), the CORDEX projections are based on the new Representative Concentration Pathways (RCPs, Moss et al., 2010), with the driving Global Climate Models (GCMs) being part of the CMIP5 experiment (Taylor et al., 2012). Only CORDEX RCM data with scenario runs available for both RCP4.5 and RCP8.5 were used in the presented analysis – the two other of the four RCP scenarios, 2.6 and 6.0, are not available for as many CORDEX simulations, as they are not defined as part of the core set of runs in CMIP5. The applied 16 CORDEX RCMs (with 32 scenario runs, as provided for both RCPs) are the result of a simulation matrix with seven different regional models driven by five different GCMs (see Table 1).

RCP4.5 can be regarded as a medium emission scenario and RCP8.5 as a high emission scenario. The names of the RCPs relate to the radiative forcing at the end of the 21st century, a measure of overall change in the Earth's energy balance due to external perturbation (Cubasch et al., 2013). RCP8.5 shows a constant rise of radiative forcing in the 21st century to around 8.5 W/m^2 in 2100, stabilizing only after the year 2200. RCP4.5 stabilizes at around 4.5 W/m^2 after 2100, with the stabilization process starting around 2070, reaching a value of around 4 W/m^2 in 2100. Radiative forcing of the SRES A1B scenario follows a pathway that is roughly midway between the pathways of RCP4.5 and RCP8.5 scenarios, reaching around 6 W/m^2 in 2100 (Cubasch et al., 2013). (Despite its name, the radiative forcing pathway of RCP6.0 is markedly below the pathway of SRES A1B, as RCP6.0 stabilizes at 6 W/m^2 after 2100 and reaches only around 5.3 W/m^2 in 2100.)

4. Methods

4.1. Hydrological modelling framework

The hydrological model is described in detail by Kling et al. (2012). The exact same model is re-used in the current study. In this section, we only give a short summary of the main features of the hydrological modelling framework of Kling et al., including:

- model structure,
- historical input data,
- calibration approach,
- evaluation approach.

The applied precipitation-runoff model COSERO (Kling et al., 2015) uses a simple, conceptual model structure, which is similar to the well-known HBV model (Bergström, 1995). For the application of the COSERO model in monthly time-steps internal temporal discretization schemes are applied. A semi-distributed spatial discretization is used. The Upper Danube basin is split into 16 sub-basins and further into overall 61 hydrological response units (HRUs) according to elevation bands. For each HRU the model determines rainfall and snowfall from precipitation and air temperature data. Snowmelt is simulated with a temperature-index approach. Actual evapotranspiration is determined from soil moisture and potential evapotranspiration. Runoff generation due to rainfall and melt-water is split into a fast component (surface flow plus interflow) and base flow. A simple glacier module is used to simulate the mass balance of major glaciers in the highest parts of the

basin. Furthermore, 14 large reservoirs and their basic operation rules are included in the model (see Fig. 1). Routing of flow in the river is not considered for monthly time-step modelling in the upper Danube basin.

The historical data used for setting up the hydrological model included precipitation data of HISTALP (Auer et al., 2007), a map showing the spatial distribution of mean annual precipitation (Kling et al., 2005, Petrovic et al., 2006), air temperature data of HISTALP stations regionalized to HRU values by use of linear regression with elevation, as well as potential evapotranspiration computed with the Turc (1961) method. Observed discharge data were collected at 16 gauges to enable calibration and evaluation of the model.

Calibration focussed on six key model parameters controlling snow melt, soil moisture storage, runoff generation and base flow recession. Automatic parameter optimization was performed with the Shuffled Complex Evolution algorithm (Duan et al., 1992) using a slightly modified version of the KGE-statistic (Gupta el al., 2009, modified by Kling et al., 2012) as objective function, to minimize the difference between simulated and observed discharge time series at 16 gauges in the period 1961–1990.

Kling et al. (2012) present a detailed evaluation of the hydrological model in independent evaluation periods 1901–1930, 1931–1960 and 1991–2007 for various measures of model performance computed at key gauges. Additional evaluation presents plots of simulated and observed seasonality in discharge for the calibration period and the ten warmest years on record (most of them occurred after 1990), as well as the simulated and observed monthly flow duration curve. In conclusion, the high agreement between the simulated discharge and historical observations over the last 100 years yields a high confidence that the model is suitable for climate change impact assessment in the Upper Danube basin.

4.2. Downscaling and bias correction of RCM data

For downscaling and bias correction of the CORDEX RCM data we present results with the well-known delta-change method (see e.g. Hay et al., 2000). The same approach was used by Kling et al. (2012) for ENSEMBLES data, and therefore the results are directly comparable (see Kling et al. for details about the spatio-temporal application of the bias correction in each month and each HRU). Historical observations of precipitation and air temperature of the period 1961–1990, which were also applied for the historical calibration of the hydrological model (see chapter 4.1), were used as a reference for the bias correction.

In addition, we also applied four other methods of bias correction with ENSEMBLES data, including linear scaling, quantile mapping, a de-trended version of quantile mapping, and moment scaling (adjusting the first and second moments of the RCM data). However, apart from some minor peculiarities when applying e.g. quantile mapping, the overall results for projected future discharge of the Danube River at Vienna are very similar to the results obtained with the delta-change method. Therefore the results with the four additional methods are not reported in this paper.

4.3. Evaluation of historical RCM simulations

Increased spatial resolution of RCM simulations with the objective of increased representation of regional climate characteristics has been formulated as one major direction of research in regional climate modelling (Leung et al., 2003, 2006). Consequently, it was one of the focuses of the large European regional climate modelling initiatives of the past decades, with RCM resolution increasing from 50 km in PRUDENCE (Christensen and Christensen, 2007) to 25 km in ENSEMBLES (Hewitt and Griggs, 2004) to 12.5 km in EURO-CORDEX (Jacob et al., 2014). Increasing performance of historical climate simulations with increasing spatial resolution can be expected due to a better description of orography and land-sea contrast and the potential of better representation of physical and dynamical processes (Christensen and Christensen, 2007). The extent to which such an improvement is successfully achieved is shown to vary considerably depending on the geographical region, the investigated variables and the spatial and temporal scales of the respective study (e.g. Wang et al., 2004; Hohenegger et al., 2008; Rauscher et al., 2010; Van Roosmalen et al., 2010; Kotlarski et al., 2014; Prein et al., 2016).

In our comparative evaluation of the performance of ENSEMBLES and CORDEX RCMs in simulating historical climate features of the Upper Danube basin we qualitatively analysed the overall mean and seasonal biases in temperature and precipitation in the entire basin and calculated, for both variables, quantitative performance measures of the reproduction of spatio-temporal patterns of mean and inter-annual variability. The evaluation period was 1961–1990. For the RCMs that do not cover the years before 1970, the period of 1971–1990 was used as alternative reference period (which is not referred to explicitly in the remainder of this article).

The equations for the quantitative performance measures, which are based on a similar approach by Sennikovs and Bethers (2009), are described in detail in Kling et al. (2012). Four sub-components of model performance (SMP) refer to the representation of mean temperature (mT) and precipitation (mP), and the (inter-annual) variability of temperature (vT) and precipitation (vP). For each RCM, each sub-component of model performance was calculated from the root mean square error (RMSE) of one of these four variables over all (61) spatial units of the hydrological model and all (12) months of the year, normalized by the median RMSE of all RCMs. One aggregate measure of model performance (MP) is determined by averaging the values of the four sub-components. For each sub-component SMP as well as for the aggregate MP, values smaller than one show that an individual RCM performs better than the median of all RCMs, and values larger than one indicate the opposite.

5. Results

5.1. Representation of historical climate

For a straightforward qualitative evaluation of RCM simulations of temperature and precipitation, long-term mean values for the entire Upper Danube basin upstream of Vienna are compared with observations (Fig. 2, left ENSEMBLES RCMs, right CORDEX RCMs). Visual comparison of mean monthly precipitation for the period of 1961–1990 (upper panel in Fig. 2) shows that the CORDEX ensemble does not include RCMs with “inverse” rainfall seasonality anymore (lowest instead of highest values in summer), as it was the case with some ENSEMBLES RCMs. Contrariwise, there is one CORDEX RCM (CLMcom_MPI) with an overestimation of summer rainfall in the basin mean that is markedly higher than in any of the ENSEMBLES RCMs. Generally, representation of seasonal precipitation has improved only marginally and still exhibits significant errors. The long-term mean precipitation bias over the entire basin ranges from −13% to +33% in the ENSEMBLES data, with a median value of +8.3%. For CORDEX data, the median of overall precipitation biases is +9.5%, with a range from −5% to +43% (the maximum value resulting again from CLMcom_MPI).

The steady increase in observed mean temperature in the historical period is captured well by all climate models (lower panel in Fig. 2). While the bias in long-term mean basin temperature for 1961–1990 in the ENSEMBLES models ranges from −2.5 °C to +2.9 °C, with a median value of −0.1 °C, the CORDEX RCMs almost only exhibit underestimation of temperature. The deviations from observed mean values range from −3.2 °C to 0.5 °C, with a median CORDEX value of −1.1 °C. Representation of the seasonal distribution of temperature is generally good in all RCMs, as already shown for the ENSEMBLES data by Kling et al. (2012).

The quantitative evaluation of spatio-temporal patterns of mean precipitation and temperature and their inter-annual variability in the RCM simulations enable a ranking of the analysed climate models

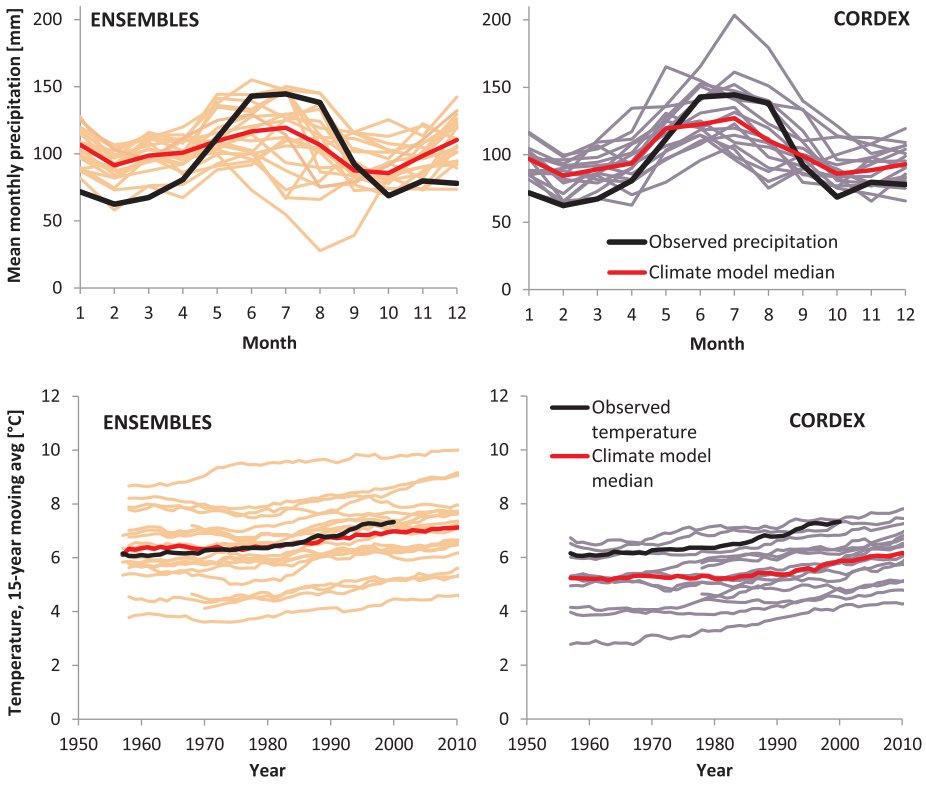


Fig. 2. Comparison of RCM data with historical observations. Top: Mean monthly precipitation of the period 1961–1990. Bottom: 15-year moving average of temperature. Left: 21 RCMs of ENSEMBLES. Right: 16 RCMs of CORDEX.

according to their ability to reproduce historical climate in the Upper Danube basin. Fig. 3 shows the computed model performance, with the best to worst performing RCMs sorted from left to right. For the aggregate measure of model performance MP (Fig. 3, top, also listed in Table 1), the CORDEX models (filled bars) show no relevant improvement as compared to the ENSEMBLES models (dashed bars). CORDEX RCMs are found both, among the best and among the worst performing models. A separate presentation of the sub-component of mean precipitation (mP, Fig. 3, middle) reveals that many CORDEX RCMs do show a better representation of spatio-temporal patterns of monthly precipitation, as the best five models in the combined ensemble are CORDEX models. However, CORDEX RCMs exhibit a lower performance with respect to mean temperature (mT, Fig. 3, bottom), with seven of the ten worst models in the combined ensemble (as also apparent in the predominant cold bias shown in Fig. 2).

Overall, the evaluation results for the Upper Danube basin show no general improvement in the accuracy of representing monthly historical climatic features in CORDEX data, as compared with ENSEMBLES, despite the increase in spatial model resolution.

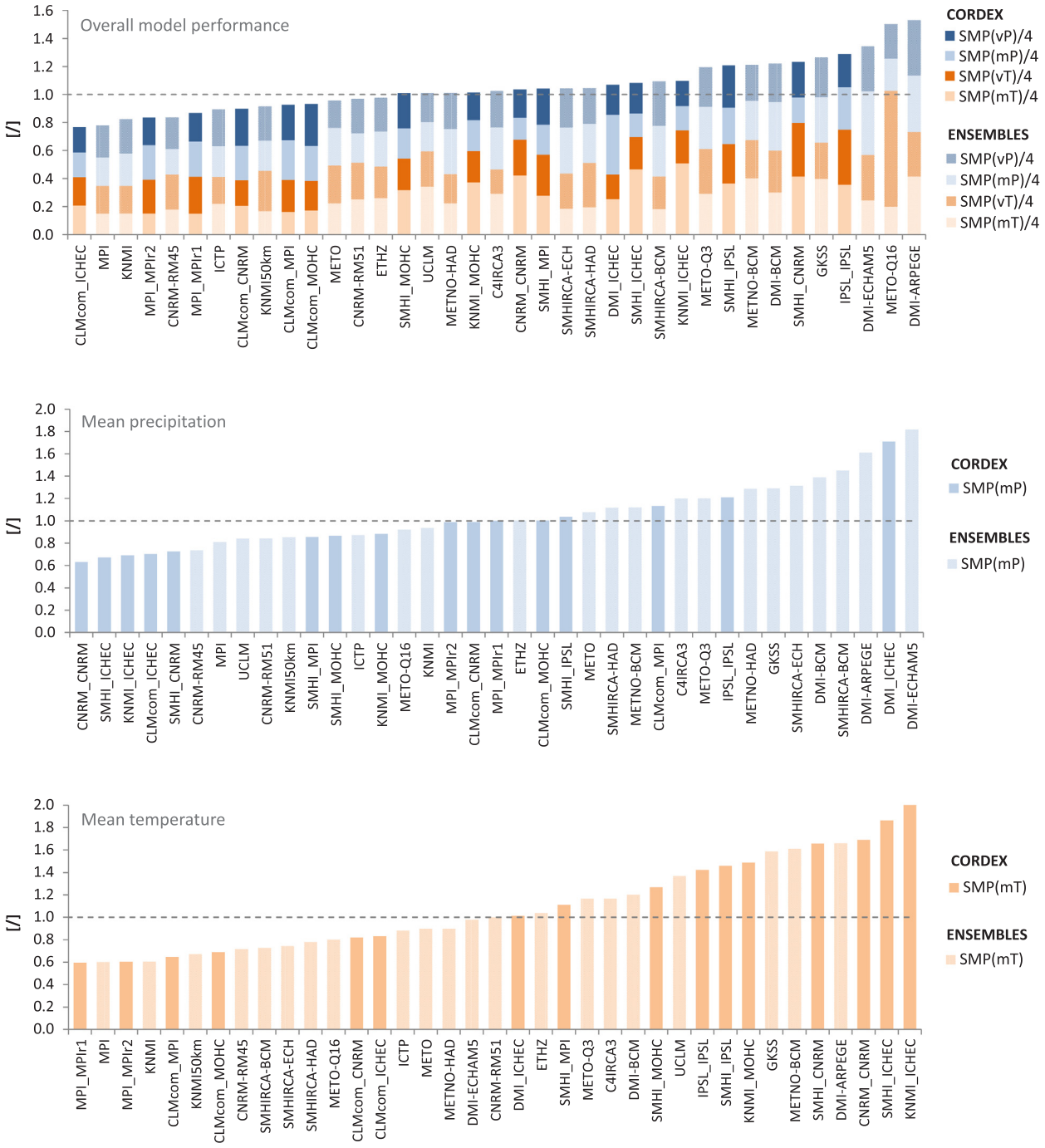
5.2. Climate change projections

The projected increase in temperature in the CORDEX scenarios for the upper Danube basin is closely related to the emission scenario (Fig. 4, top). RCP4.5 scenarios show lower increases ranging from 2 °C to 3.5 °C in the basin average until the end of the 21st century. Projections under RCP8.5 are markedly higher, with changes until the end of the century in the range of 3.5 °C to 6.2 °C. Interestingly, the entire range of temperature change projections of both CORDEX RCP scenarios is very similar to the range of ENSEMBLES projections, even though they are based on only one (medium) SRES emission scenario.

The differences between the two CORDEX emission scenarios become apparent only after 2050. The median temperature change signal of the period 2021–2050, as compared with 1961–1990, is almost equal for RCP4.5 (1.4 °C, Table 2) and for RCP8.5 (1.5 °C), and also for the ENSEMBLES median (1.5 °C). For the period 2071–2100, the ENSEMBLES median temperature increase of 3.2 °C is midway between the two CORDEX scenarios of RCP4.5 (2.3 °C) and RCP8.5 (4.1 °C). For different seasons of the year, the relations between the CORDEX projections with different RCPs and the ENSEMBLES projections are similar to the relations in these annual changes (Table 2).

In the CORDEX precipitation projections (Fig. 4, bottom), no clear difference between the different emission scenarios is found. After the middle of the 21st century, almost all CORDEX projections show an increase in precipitation compared to 1961–1990, with values of some models ranging over 20%. These projected CORDEX precipitation increases are higher than the highest projected changes in the ENSEMBLES data. The ENSEMBLES projections also include results with considerably decreasing precipitation, so that in general the range of future precipitation with ENSEMBLES data is below the CORDEX range. The higher precipitation in CORDEX data, as compared with ENSEMBLES, is more pronounced towards the end of the century, in the period 2071–2100. Seasonally, CORDEX precipitation projections are higher than ENSEMBLES results in winter and spring, for the period of 2021–2050, and in winter and summer, for the period of 2071–2100 (Table 2).

This shift towards higher precipitation projections from ENSEMBLES to CORDEX is also clearly visible when change signals of 30-year means of temperature and precipitation are plotted against each other (Fig. 5), especially for the far future period of 2071–2100 and RCP8.5. The GCM grouping in Fig. 5 also confirms, for CORDEX data, the finding by Kling et al. (2012, for ENSEMBLES data) that the level of projected temperature change can be related to the driving GCM, while precipitation projections vary considerably between RCM simulations with the same driving GCM.


Overall model performance
[/]
CORDEX
SMP(vP)/4
SMP(mP)/4
SMP(vT)/4
SMP(mT)/4
ENSEMBLES
SMP(vP)/4
SMP(mP)/4
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SMP(mT)/4
CLMcom_ICHEC MPI KNMI MPI_MPIr2 CNRM-RM45 MPI_MPIr1 ICTP CLMcom_CNRM KNMI50km CLMcom_MPI CLMcom_MOHC METO CNRM-RM51 ETHZ SMHI_MOHC UCLM METNO-HAD KNMI_MOHC C4IRCA3 CNRM_CNRM SMHI_MPI SMHIRCA-ECH SMHIRCA-HAD DMI_ICHEC SMHI_ICHEC SMHIRCA-BCM KNMI_ICHEC METO-Q3 SMHI_IPSL METNO-BCM DMI-BCM SMHI_CNRM GKSS IPSL_IPSL DMI-ECHAM5 METO-Q16 DMI-ARPEGE
Mean precipitation
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SMP(mP)
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CNRM_CNRM SMHI_ICHEC KNMI_ICHEC CLMcom_ICHEC SMHI_CNRM CNRM-RM45 MPI UCLM CNRM-RM51 KNMI50km SMHI_MPI SMHI_MOHC ICTP KNMI_MOHC METO-Q16 KNMI MPI_MPIr2 CLMcom_CNRM MPI_MPIr1 ETHZ CLMcom_MOHC SMHI_IPSL METO SMHIRCA-HAD METNO-BCM CLMcom_MPI C4IRCA3 METO-Q3 IPSL_IPSL METNO-HAD GKSS SMHIRCA-ECH DMI-BCM SMHIRCA-BCM DMI-ARPEGE DMI_ICHEC DMI-ECHAM5
Mean temperature
[/]
CORDEX
SMP(mT)
ENSEMBLES
SMP(mT)
MPI_MPIr1 MPI MPI_MPIr2 KNMI CLMcom_MPI KNMI50km CLMcom_MOHC CNRM-RM45 SMHIRCA-BCM SMHIRCA-ECH SMHIRCA-HAD METO-Q16 CLMcom_CNRM CLMcom_ICHEC ICTP METO METNO-HAD DMI-ECHAM5 CNRM-RM51 DMI_ICHEC ETHZ SMHI_MPI METO-Q3 C4IRCA3 DMI-BCM SMHI_MOHC UCLM IPSL_IPSL SMHI_IPSL KNMI_MOHC GKSS METNO-BCM SMHI_CNRM DMI-ARPEGE CNRM_CNRM SMHI_ICHEC KNMI_ICHEC

Fig. 3. Evaluation of 16 CORDEX RCMs (dark colour bars) and 21 ENSEMBLES RCMs (light colour bars), sorted from left to right with decreasing model performance (smaller values indicate better performance). Top: RCMs sorted according to overall model performance (MP), with colours showing sub-components (SMP) for reproducing spatio-temporal patterns of mean (m) and variability (v) in temperature (T) and precipitation (P). Middle: RCMs sorted according to the sub-component of mean precipitation, SMP(mP). Bottom: RCMs sorted according to the sub-component of mean temperature, SMP(mT).

5.3. Discharge projections

Scenario simulations driven by climate projections from the CORDEX ensemble show a clear pattern of change in seasonality of future discharge at Vienna, albeit with a large range of results with single ensemble members (Fig. 6). Winter discharge increases, the seasonal discharge peak in spring occurs earlier, and summer discharge decreases. These elements of change in future seasonal discharge are shown by all or almost all individual projections, to different extents, with all three effects being more pronounced in a more distant future (2071–2100) than in an earlier period (2021–2050).

These findings with the most recent climate modelling data of the CORDEX initiative generally confirm projected patterns of changes in discharge seasonality found in previous studies, both on already observed trends (Fürst et al., 2007; Pekarova et al., 2008) and on future projections (e.g. Stanzel and Nachtnebel, 2010; Koch et al., 2011; Prasch et al., 2011; Kling et al., 2012; Stagl and Hattermann, 2015; Wagner et al., 2017). Results with ENSEMBLES RCMs, shown as orange shading in Fig. 6, do not only show a very similar seasonal pattern of change but also exhibit a comparable range of projections, despite the differences in assumed greenhouse gas emission scenarios. The corresponding distributions of projection results with ENSEMBLES and

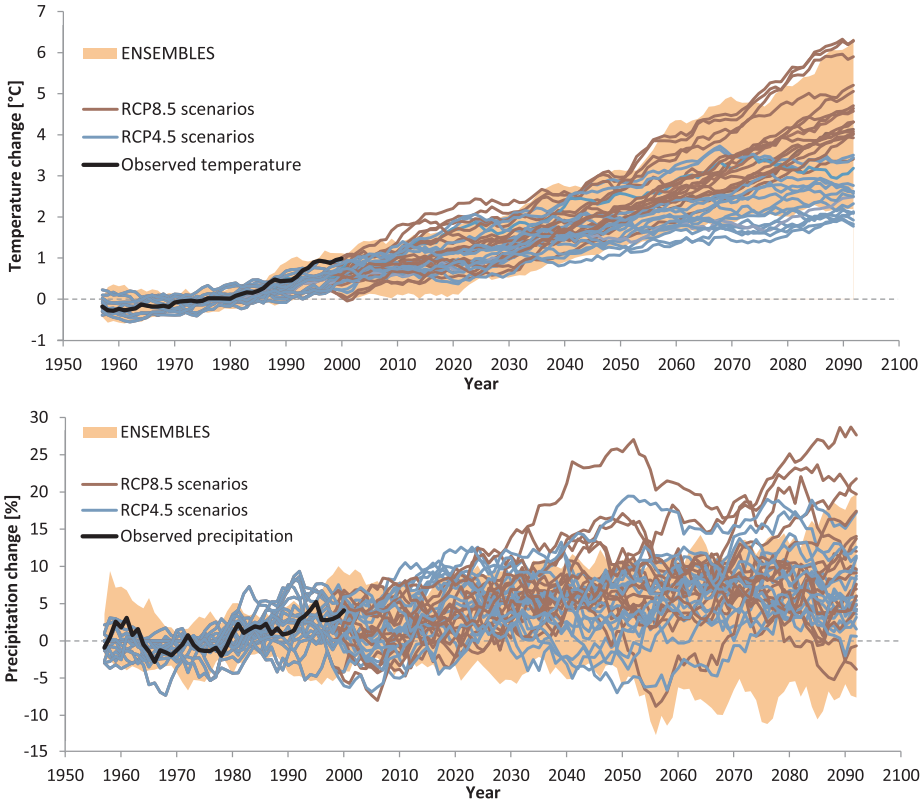

Fig. 4. Climate change projections for the upper Danube basin as compared to 1961–1990. 15-year moving averages of temperature change (top) and precipitation change (bottom). Black: observation; blue: CORDEX RCP4.5 scenarios; red: CORDEX RCP8.5 scenarios. Orange shading: range of ENSEMBLES results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Ensemble medians of seasonal and annual climate change signals for mean temperature (ΔT) and mean precipitation (ΔP) in the catchment area of the Upper Danube, and for discharge (ΔQ) of the Danube at Vienna, for the two future periods. Climate change signals in relation to the reference period 1961–1990.

			2021–2050					2071–2100				
			Spring	Summer	Autumn	Winter	Annual	Spring	Summer	Autumn	Winter	Annual
ΔT	ENSEMBLES	A1B	1.3	1.6	1.6	1.8	1.5	2.7	3.7	3.1	3.6	3.2
[°C]	CORDEX	RCP4.5	1.0	1.5	1.3	1.7	1.4	2.1	2.3	2.4	2.7	2.3
	CORDEX	RCP8.5	1.3	1.5	1.6	1.6	1.5	3.7	4.1	4.1	4.7	4.1
ΔP	ENSEMBLES	A1B	5.0	2.6	7.3	6.3	4.1	10.1	−9.4	7.5	8.4	4.5
[%]	CORDEX	RCP4.5	10.4	−1.2	2.7	9.7	4.9	13.0	2.6	5.7	13.7	6.9
	CORDEX	RCP8.5	12.9	1.7	7.6	13.1	6.5	17.7	−3.7	10.4	20.5	9.3
ΔQ	ENSEMBLES	A1B	−4.3	−12.0	−1.9	8.4	−3.9	−4.3	−32.5	−14.4	13.4	−12.0
[%]	CORDEX	RCP4.5	2.2	−11.8	−5.7	12.8	−1.8	1.8	−13.2	−5.5	17.9	−1.4
	CORDEX	RCP8.5	4.3	−9.6	−0.8	17.1	1.3	−0.9	−24.8	−12.2	29.2	−5.1

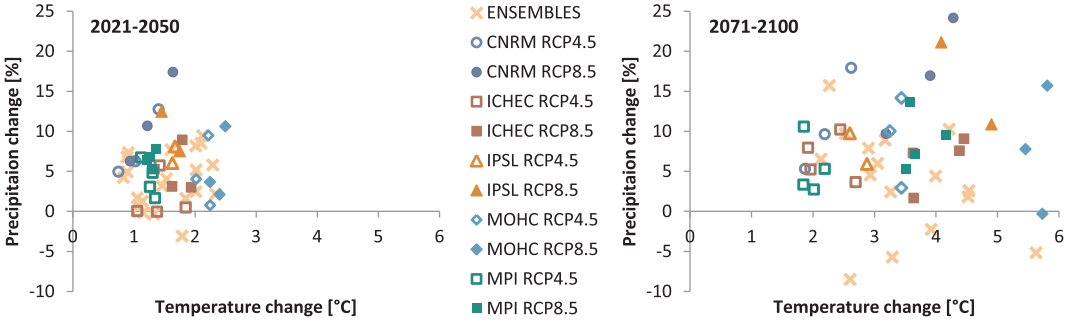

Fig. 5. RCM projections of change in precipitation vs. temperature for 2021–2050 and 2071–2100 (as compared to 1961–1990). Symbols for CORDEX RCMs grouped by driving GCM. Orange crosses: ENSEMBLES RCMs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

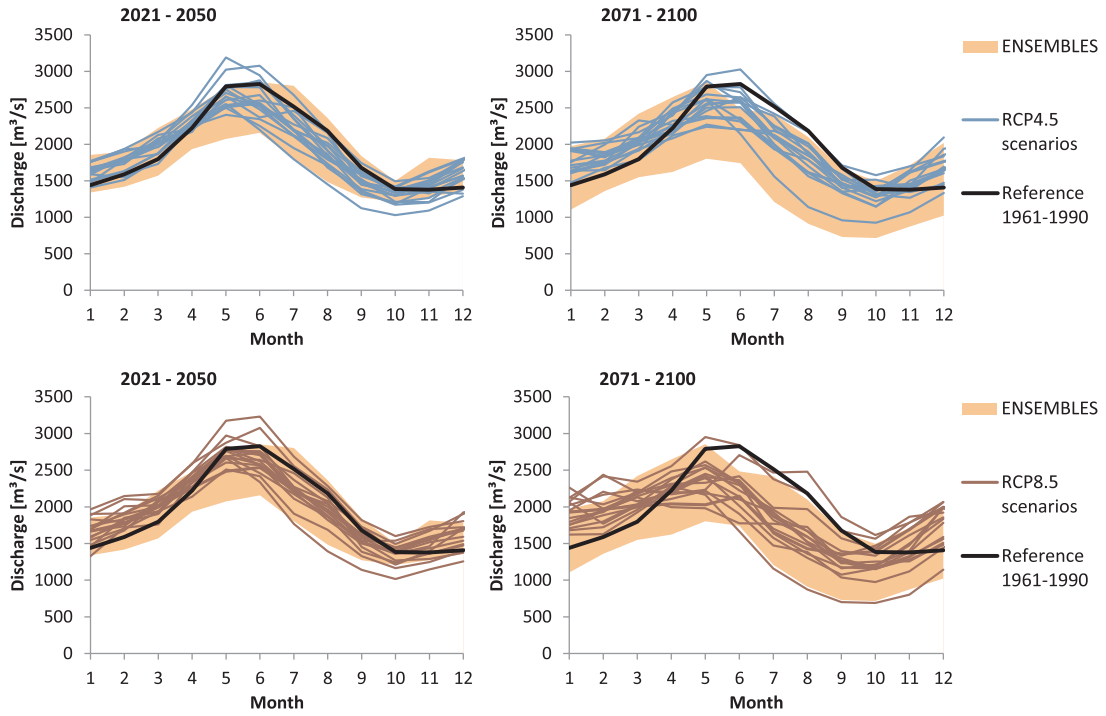

Fig. 6. Seasonal discharge projections for the Danube at Vienna for 2021–2050 (left) and 2071–2100 (right). Black: reference period 1961–1990; blue (top): CORDEX RCP4.5 scenarios; red (bottom): CORDEX RCP8.5 scenarios. Orange shading: range of ENSEMBLES results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

CORDEX data are even clearer in a comparison of ensemble median values (Fig. 7 and Table 2). Differences between ENSEMBLES and CORDEX results are discernible for spring and, to a lesser extent, for winter, for the period of 2021–2050, and for winter and summer, for the period of 2071–2100. These differences can directly be related to higher precipitation projections for these seasons in the respective periods in the CORDEX data (see section 5.2 and Table 2). For the summer season in the far future period 2071–2100 the additional effect of rising temperatures becomes evident: RCP8.5 projections of lower precipitation and higher temperature lead to markedly lower discharge than in the RCP4.5 scenario, with a median almost as low as in the ENSEMBLES results that are related to even lower summer precipitation.

In the annual mean, smaller changes in discharge are projected by the CORDEX scenarios than by the ENSEMBLES scenarios (Table 2). For the period of 2021–2050, CORDEX results show almost no change, with a median decrease of less than −2% for RCP4.5 scenarios and a median increase below 2% for RCP8.5 scenarios, compared to a median decrease of almost −4% for the ENSEMBLES scenarios. For 2071–2100, CORDEX projections show decreasing mean annual discharge of −1.4% in the median of RCP4.5 scenarios and −5.1% in the RCP8.5 scenarios, both markedly lower than the median decrease in ENSEMBLES projections of −12% for the end of the 21st century.

An analysis of the impact on more extreme hydrological conditions is presented in Table 3, specifying changes in low flow values (related to an exceedance probability of 90%, denominated Q90 in Table 3) and high flow values (related to an exceedance probability of 10%, denominated Q10). Note that all values refer to monthly mean discharges, representing low and high flow periods rather than extreme events. Projections based on ENSEMBLES data generally show a decrease in both, high flow and low flow values, over a large range of model simulations. Only for Q90 and the near future in 2021–2050, the upper quartile value shows a small increase.

In the CORDEX projections, high flow also tends to decrease, with only the upper quartile of the RCM ensemble for Q10 showing small increases. Median Q10 decreases are lower than in the ENSEMBLES projections, which is mainly a result of the higher precipitation in CORDEX projections. For the far future period 2071–2100, the stronger decrease of Q10 in the RCP8.5 projections shows combined effects of precipitation and temperature: the shift to earlier high flow months

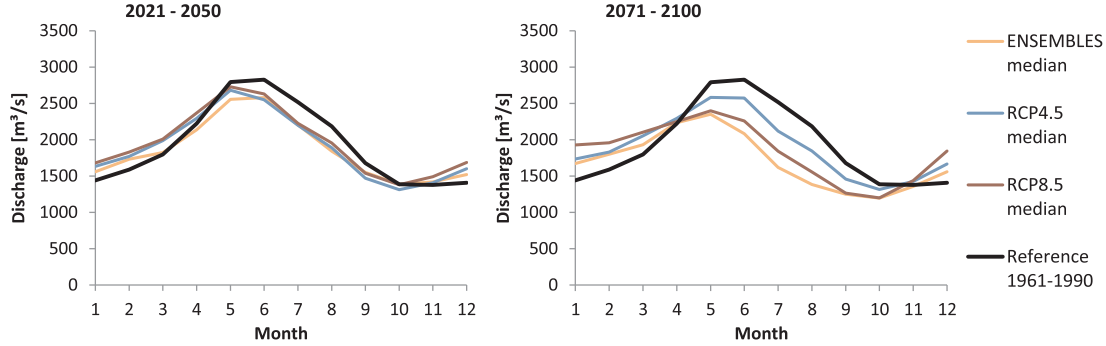

Fig. 7. Median seasonal discharge projections based on different RCM ensembles for the Danube at Vienna for 2021–2050 (left) and 2071–2100 (right).

Table 3
Projected changes in monthly high flow (exceedance probability of 10%, Q10) and monthly low flow (exceedance probability of 90%, Q90) of the Danube at Vienna. Median, lower quartile and upper quartile values of the distribution of RCM model ensemble results, for the two future periods. Climate change signals in relation to the reference period 1961–1990.

		2021–2050		2071–2100	
		Δ Q10 [%]	Δ Q90 [%]	Δ Q10 [%]	Δ Q90 [%]
ENSEMBLES	lower quartile	−10.5	−5.8	−20.6	−25.0
	median	−6.5	−0.7	−9.3	−10.2
	upper quartile	−1.0	3.0	−5.8	−1.8
CORDEX RCP4.5	lower quartile	−5.0	−7.3	−4.8	−5.0
	median	−2.0	−0.1	−2.2	0.4
	upper quartile	0.1	1.5	3.1	2.5
CORDEX RCP8.5	lower quartile	−1.6	−3.3	−9.6	−11.1
	median	0.6	3.4	−5.3	−7.4
	upper quartile	2.3	6.4	−0.1	1.8

(from early summer to late spring) and the generally lower discharge in the high flow months is related to increasing spring and decreasing summer precipitation in the RCP8.5 simulations and to earlier snow melt and higher evaporation due to a stronger temperature increase than in RCP4.5.

In the CORDEX model median, low flow does not change considerably, in contrast to the significant decrease in ENSEMBLES Q90 results for 2071–2100. The generally higher Q90 in the CORDEX projections than with ENSEMBLES data results from higher summer precipitation, leading to higher discharge levels in autumn, the future principal low flow period. (Currently, low flow occurs mainly during late autumn and winter, but shifts to earlier months due to increasing winter discharge in the future projections). Compared with RCP4.5, the RCP8.5 scenarios for the far future show more pronounced decreases in low flow discharge due to lower summer precipitation and higher summer temperature.

The typical change pattern of increasing discharge in winter and decreasing discharge in summer is apparent also in smaller tributary catchments with very distinct hydrological regimes, albeit with different magnitudes. Fig. 8 shows projected changes – only for the period 2071–2100, with clearer impacts – for the Upper Inn in the highest Alpine region, the lowland Naab, and the Traun, located in the lower Alps and alpine foothills (see Fig. 1). Seasonal changes are more pronounced in the Upper Inn and Traun catchments with important snow processes. In these catchments, and particularly for the high alpine Upper Inn, also the differences between the cooler RCP4.5 scenarios and the warmer RCP8.5 scenarios are more distinct, with markedly higher winter discharge and lower summer discharge in RCP8.5. In the lowland Naab catchment, the projected changes are generally less pronounced, but here the CORDEX results show reduced uncertainty compared with ENSEMBLES. While the ENSEMBLES range includes models projecting considerable decreases in winter discharge, no such projections are included in the CORDEX ensemble, which can be attributed to higher precipitation projections in the CORDEX climate model data.

6. Discussion

6.1. Sources of change between scenario generations

The presented results show, in general, a high consistency between the results with the most recent, high resolution RCM simulations of the CORDEX initiative and the results based on the previous generation of RCMs of the ENSEMBLES initiative, but also reveal some specific differences. Differences in the results of successive climate impact assessments can generally be expected due to development in all three elements of the impact modelling chain, at the GCM level, at the RCM level, and at the impact model level. Comparison between results can further be complicated by changes in the reference periods or the investigated future periods. By exactly replicating a previous hydrological modelling framework, including downscaling and bias correction methods and periods of analysis, the presented study excludes changes at the impact modelling level.

The attribution of emerging simulation differences to specific changes at the RCM or GCM level could be investigated in detail if the same RCM were driven by different generations of the same GCM, or, inversely, the same GCM would drive different generations of the same RCM. However, no such combination is available from the simulation matrices of ENSEMBLES and CORDEX (see Table 1). The GCMs driving CORDEX RCMs are mostly others than the driving GCMs in ENSEMBLES, and the few GCM types included in both regional modelling initiatives have been developed in many aspects from the previous CMIP3 generation to the current CMIP5 generation (Knutti et al., 2013). The same is true for the development of RCMs included in ENSEMBLES and CORDEX, which includes changes in coding, parameterization and general physical process representation, many related to the increase in spatial resolution (e.g. Christensen et al., 2007; Samuelsson et al., 2015).

Possible effects of the changes at the GCM level can be inferred from general comparison studies of CMIP3 and CMIP5 simulations of historical climate (e.g. Kumar et al., 2014; Koutroulis et al., 2016) and future projections (e.g. Knutti and Sedlacek, 2013; Woldemeskel et al., 2016). Evidence for specific influences of changes at the RCM level is found in climatological research comparing ENSEMBLES and CORDEX data (Kotlarski et al., 2014; Smiatek et al., 2016) and comparing different resolution CORDEX simulations (Torma et al., 2015; Prein et al., 2016). Relevant aspects of the mentioned studies for the GCM and RCM levels are discussed in the next two chapters.

6.2. Historical climate in high resolution CORDEX RCMs

As discussed in Section 4.3, one expected result of increased horizontal resolution of RCMs, as achieved in the development from ENSEMBLES (25 km resolution) to CORDEX EUR-11 (12.5 km resolution) is an improved representation of the historical climate in the climate model simulations, especially over complex terrain as in the alpine Upper Danube basin. For monthly temperature, however, the RCM performance did not improve, but rather deteriorate, and almost all CORDEX models exhibit a cold bias. The notable cold bias of CORDEX EUR-11 simulations was also shown by Kotlarski et al. (2014) and Smiatek et al. (2016) for their (larger) Alpine domains and by Romanowicz et al. (2016) for Poland. Smiatek et al. (2016) argue that the cold bias is not related to the driving GCMs but rather with the RCMs, as reanalysis-driven CORDEX simulations lead to a comparable bias range, and that the higher spatial resolution might play a role. This could also be inferred from the fact that both, ENSEMBLES and CORDEX data sets, show increasing cold bias at higher elevations, as higher spatial resolution also leads to better topographic representation

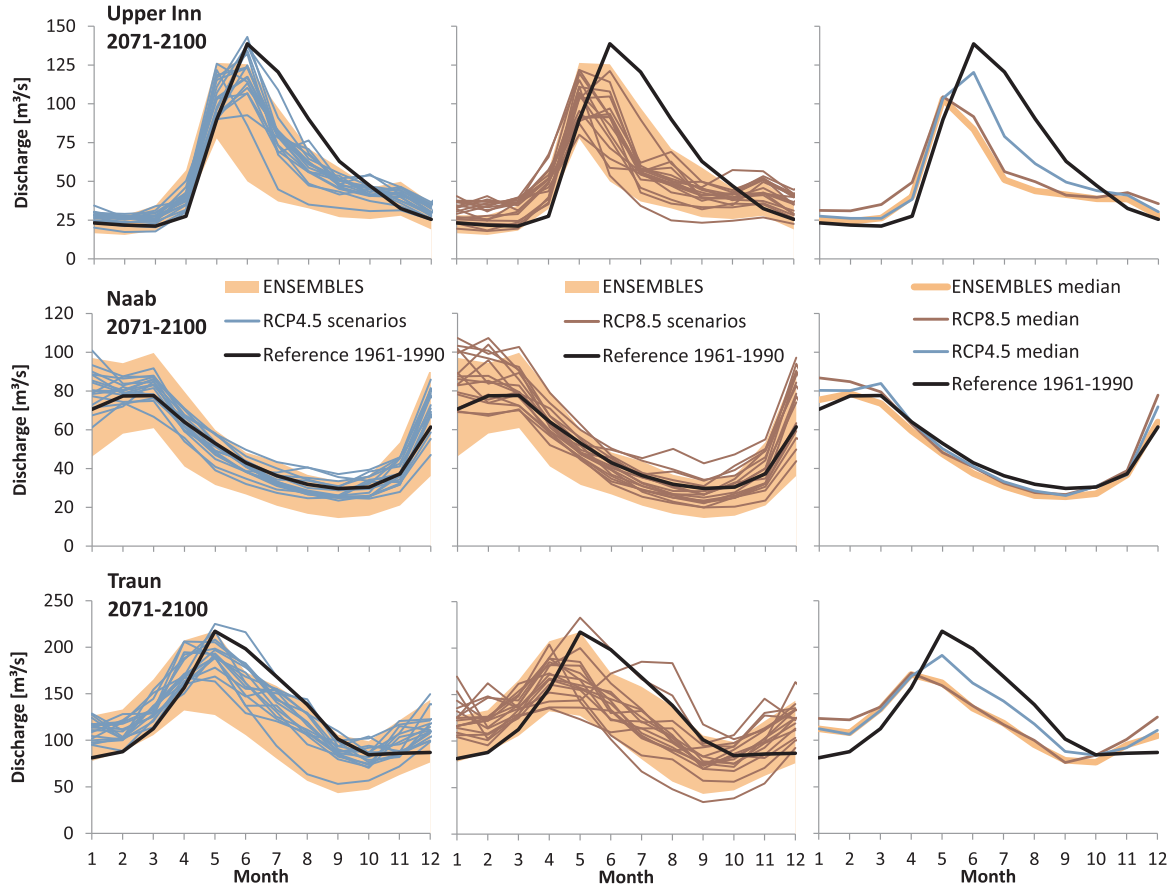

Fig. 8. Seasonal discharge projections for Danube tributary catchments for 2071–2100. Top row: Upper Inn; middle row: Naab; bottom row: Traun. Black: reference period 1961–1990; blue: CORDEX RCP4.5 scenarios (left column) and median (right column); red: CORDEX RCP8.5 scenarios (middle column) and median (right column); orange shading and line: range (left and middle column) and median (right column) of ENSEMBLES results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of the high alpine ridges, and therefore higher elevations in the RCM grid cells. Kotlarski et al. (2014), however, show that only for some individual RCMs (by SMHI and KNMI) high resolution EUR-11 simulations are colder than the coarse EUR-44 simulations, and that there is no general systematic decrease of simulated temperature with increased horizontal resolution.

For precipitation, which for the Upper Danube model domain is represented slightly better in some CORDEX EUR-11 simulations of historical climate than in ENSEMBLES simulations, several authors describe an increase in simulated RCM precipitation with increasing resolution (Rauscher et al., 2010; Van Roosmalen et al., 2010; Kotlarski et al., 2014; Torma et al., 2015; Prein et al., 2016). Prein et al. (2016) also relate the higher precipitation along the north-western fringe of the Alps – due to orographic effects induced by a better representation of topography in CORDEX EUR-11 RCMs – with reduced precipitation bias on a local scale (grid cell by grid cell). Similar improvements in the representation of precipitation characteristics in the Alps due to better topographical forcing (related to higher precipitation) in models with higher resolution, on different spatial scales of analysis, were reported by Torma et al. (2015) for an ensemble of EURO-CORDEX and MED-CORDEX models. Kotlarski et al. (2014), on the other hand, also show higher precipitation in the CORDEX EUR-11 than in the EUR-44 simulations, but relate the higher precipitation with higher precipitation bias (higher overestimation) in the EUR-11 simulations for regional averages.

Clearly, detection of added value of increased horizontal resolution for the simulation of historical climate depends on the spatial and temporal scales of the analysis, and also on the applied observational data set. This is also apparent from diverging results on the development of representation of historical climate in GCMs by Kumar et al. (2014) and Koutroulis et al. (2016) – but the general pattern of moderate improvement in the simulation of precipitation from CMIP3 to CMIP5, and no relevant improvement in the representation of temperature is shown for Europe already at the GCM level.

For the spatial and temporal scales of the Upper Danube hydrological model we observed a small improvement in the representation of precipitation by the CORDEX RCMs. At the same time, air temperature representation deteriorated compared to ENSEMBLES. Therefore, we see no overall improvement in the reproduction of observed climate in CORDEX EUR-11 simulations in comparison to ENSEMBLES (thus agreeing with the conclusions of Kotlarski et al., 2014; Smiatek et al., 2016). The fact, however, that the small advances in the simulation of precipitation can be related to the increase in model resolution, suggests possible further progress along this line of climate research in the future.

6.3. *Future projections and projection uncertainty*

The most notable difference between the CORDEX and ENSEMBLES projections for the 21st century is the higher precipitation and resulting higher discharge in the CORDEX EUR-11 RCMs. While differences between CORDEX and ENSEMBLES projections can result from general climate model development (Ylhäisi et al., 2015) and also from the differences in underlying concentration pathways between SRES and RCP scenarios, there is indication that the higher precipitation projections can also be related to the higher spatial model resolution. Torma

et al. (2015) show that projected precipitation for the end of the 21st century over the central alpine mountains is higher in the CORDEX EUR-11 RCMs than in EUR-44, especially in summer (as in our comparison with ENSEMBLES). Fischer et al. (2015), for ENSEMBLES, and Giorgi et al. (2016), for CORDEX, attribute higher precipitation projections over high Alpine elevations in summer in RCMs (as compared to GCMs) to increased convective rainfall, and Giorgi et al. (2016) find confirmation for the projected changes in this mechanism in convection-resolving simulations and in consistency with some observed trends. These results suggest that the higher precipitation projections in the high-resolution CORDEX EUR-11 data, as compared to ENSEMBLES data, stem from a better process representation, indicating improved climate projections for impact research in the alpine domain.

However, the applied RCMs of CORDEX and ENSEMBLES are so-called "ensembles of opportunity", assembled based on many un-scientific factors (funding, computational resources, dissemination to impact research, etc.). As Tebaldi and Knutti (2007) point out, the distribution of climate models therefore changes from one ensemble to the subsequent, leading to changes in the results even if the knowledge of the climate system had not changed. Changes in the climate model distribution affect the derived ensemble medians and the range of included model projections. This can also be one of the reasons for the unreduced uncertainty range of CORDEX precipitation and discharge projections, as compared to ENSEMBLES (the range of temperature projections for each single RCP scenario is actually smaller than the range in ENSEMBLES SRES A1B projections). For the driving GCMs, a limited reduction in the projection uncertainty from CMIP3 to CMIP5 was achieved for precipitation, but not for temperature (Woldemeskel et al., 2016). A reduction of the range of uncertainty in climate projections can be regarded as another important – and theoretically achievable – objective of climate model development (Hawkins and Sutton, 2009), that has not yet been achieved for the presented impact modelling application for the Upper Danube River. Knutti and Sedlacek (2013) do not expect the spread in climate model projections to decrease in the near future, but emphasize that the confidence in climate simulations can still grow, if more of the relevant processes are captured – as described above for convective precipitation over the alpine parts in the Upper Danube basin.

6.4. Implications for impact research and water management

From the point of view of hydrological impact research, the above discussed aspects are important to consider, but they require further research in climate modelling. The two main questions for hydrology and water management are if the results of the analyses of development from ENSEMBLES to CORDEX (1) indicate a preference for applying one of the two climate data sets in present impact research, and (2) imply the need for further impact research with future generations of climate models.

Despite the shortcomings in achieving better representation of historical climate, we advocate the use of the more recent CORDEX climate data for current impact research for Europe. The CORDEX initiative accomplished important improvements in the dissemination of standardized data products, which facilitates the widespread use of the data and will contribute to making CORDEX scenarios a general reference in the coming years. As CORDEX RCMs are driven by CMIP5 GCMs and projections are based on the latest RCP emission scenarios, results are comparable with current GCM-based studies. Moreover, there are indications that precipitation processes are represented better in CORDEX simulations, as discussed above, leading to higher confidence in related CORDEX projections.

Regarding future generations of climate models, there is some controversy within the climate research community if models with ever-increased horizontal resolution for ultimately "seamless" weather and climate prediction systems should be aspired or not, and under which institutional arrangements (e.g. Shukla et al., 2009; Held, 2014; Katzav and Parker, 2015). At the same time, new generations of climate model results are being produced, e.g. in the PRIMAVERA project and the HighResMIP initiative that aim at high-resolution GCMs (Haarsma et al., 2016), and new data will become constantly available to the impact community. Improvement in process representation, and thus confidence in projected scenarios, can be expected from these initiatives. Furthermore, as human greenhouse gas emissions will change in the future, for better or for worse, projections of climate change will change as well, independent of progress in climate science. Further advances in the smooth transfer of data and knowledge from climate modelling to impact modelling can be expected from initiatives that include the needs of climate data users in the conception of climate data production, such as the ongoing projects Copernicus Climate Change Service (C3S, Raoult et al., 2017) and PRIMAVERA (Palin et al., 2017), and will continue to make updates of impact studies more efficient. Therefore hydrological scenarios should be updated regularly, ideally keeping the hydrological framework unchanged as in the study presented here.

The confirmation of the general pattern of future changes in discharge characteristics, however, clearly implies that more detailed or less uncertain information on climate impact in the Upper Danube basin is no prerequisite for the preparation of tangible adaptation pathways. Uncertainty in climate and climate impact prediction cannot be reduced beyond a certain level, despite all efforts in research, so that robust adaptation strategies need to be established that promise success for a range of alternative futures (Dessai et al., 2009). As for climate change mitigation, "wait and see" (or "predict with higher accuracy, then act") is no option for adaptation in water management, as many adaptation measures have long-term planning horizons and might not be implemented quickly enough if their preparation starts in a future with better knowledge on climate change impact (Knutti and Rogelji, 2015). For the Upper Danube, the main patterns of changes in the discharge regime that can be expected in a warming climate – and the related uncertainties – are clear, as confirmed again by the present study, and water management can act accordingly.

7. Conclusions

A large ensemble of latest generation RCM data from the CORDEX initiative, with a horizontal spatial resolution of 12.5 km and based on RCP greenhouse gas emission scenarios, was applied in a hydrological impact study of the Upper Danube basin upstream of Vienna. The hydrological modelling set-up and the downscaling and bias correction of climate model data was replicated from a previous assessment applying a large ensemble of ENSEMBLES RCM data, with a resolution of 25 km and based on the SRES A1B emission scenario. Maintaining the identical data processing and impact modelling framework allowed systematic analyses of the development of climate change scenarios from one generation of RCMs to the next.

The overall representation of historical climatic features in CORDEX data shows no relevant improvement compared with ENSEMBLES, despite the increase in spatial model resolution, for the analysed region and spatio-temporal scales. In several CORDEX RCMs, precipitation bias is lower than in ENSEMBLES RCMs, with remaining deficits in the representation of rainfall seasonality. Temperature representation has deteriorated compared to ENSEMBLES in some CORDEX simulations, with a shift towards a generally prevailing cold bias in the CORDEX ensemble.

The range of projections of temperature increase in CORDEX data under RCP emission scenarios is very similar to the range projected by the ENSEMBLES RCMs under SRES A1B emission scenarios, with RCP4.5 scenarios in the lower and RCP8.5 scenarios in the upper part of the range. The range of precipitation change projections in CORDEX data is also similar to the range projected by the ENSEMBLES RCMs, but with a stronger tendency towards precipitation increase. The higher precipitation in CORDEX projections might result from better process

representation related to higher horizontal RCM resolution, suggesting higher confidence in the new climate scenarios.

Due to higher precipitation projections, the expected decrease in future mean annual discharge of the Danube at Vienna is considerably lower with CORDEX data (−3.3% in the median of all analysed scenarios for the period of 2071–2100) than with ENSEMBLES data (−12%). Typical patterns of change in discharge seasonality connected with a warming climate that were already identified in previous studies – increasing winter discharge and decreasing summer discharge – are confirmed again with the new CORDEX data.

The analysed specific differences between the results with two consecutive generations of climate model simulations show that regular updates of hydrological impact modelling are productive and should be continued with climate data provided by future climate research initiatives. Rigorous replication of the hydrological modelling framework, as described in the presented study, enables detailed analyses of the development of climate change scenarios. The general confirmation of expected future tendencies in the discharge regime shows the need for timely formulation of adaptation strategies for water management in the Upper Danube basin.

8. Declaration of interests

None.

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